US Army Corps
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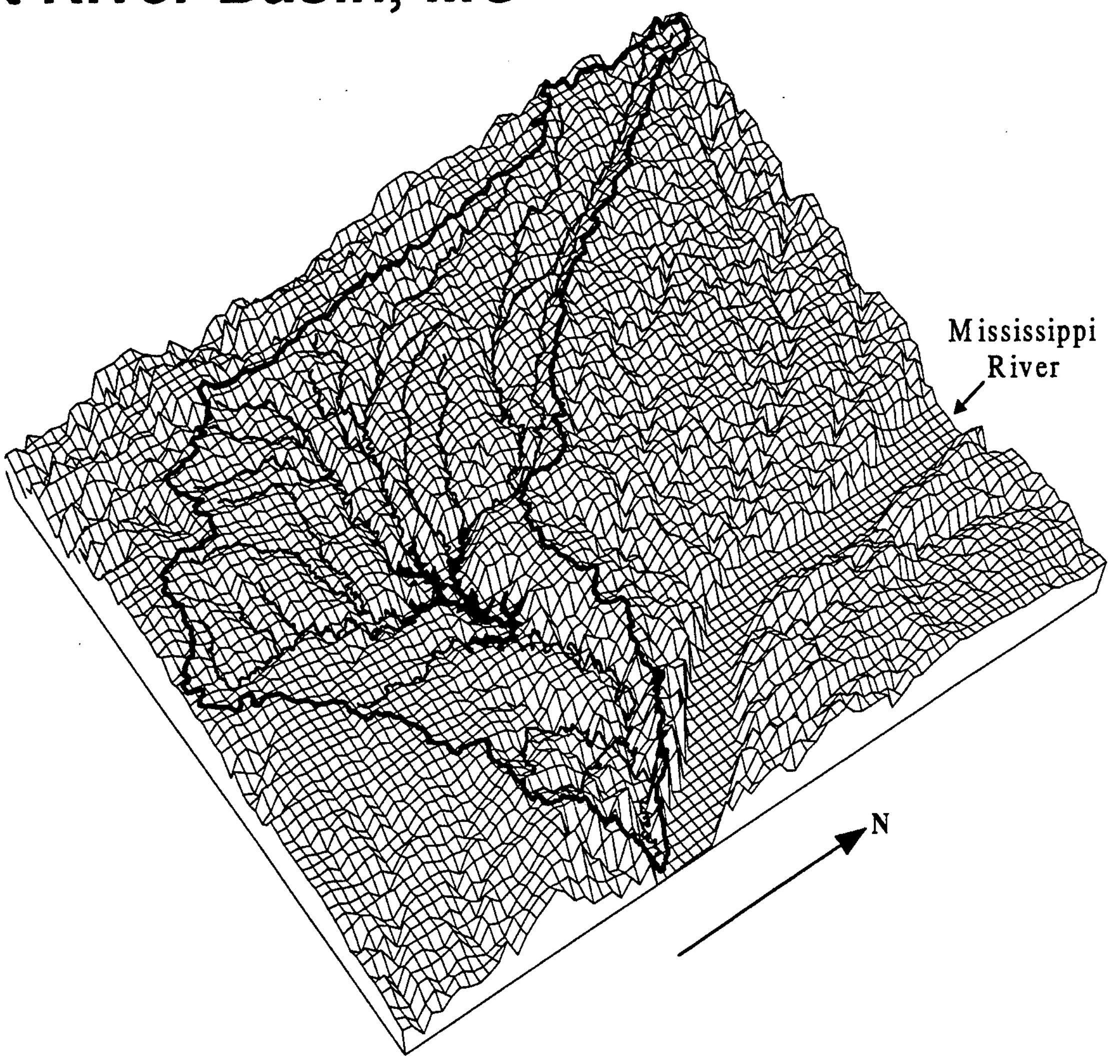
Hydrologic Engineering Center

A Pilot Application of Weather Radar-Based Runoff Forecasting, Salt River Basin, MO



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HEC has developed the program modClark to take a first step in the integration of spatially distributed watershed data into applied hydrology. modClark is based conceptually on Clark's 50-year-old unit hydrograph technique and uses Next Generation Weather Radar (NEXRAD) data and digital elevation models (DEM). This report documents an example application of the modClark modeling method on the Salt River Basin of Missouri.

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Chapter 1

Introduction

1.1 Purpose

The modClark procedure is a new modeling approach that uses WSR-88D weather-radar (NEXRAD) data as a distributed input to rainfall-runoff modeling. A detailed description of the modClark procedure is given in Chapter 3. The procedure was developed as part of the Water Control Data System (WCDS) modernization effort (USACE 1995e) and testing is in progress with a basin in the Corps' Tulsa District. To encourage the use of NEXRAD data and rainfall-runoff modeling for forecasting inflows to the Mississippi River Stage Forecast Model, CECW-EH-Y provided funding to promote a demonstration project. The project was to provide an example application for field offices. Thus, the intent of this document is to demonstrate the radar rainfall and runoff modeling process; the calibration and application of the hydrologic models was only taken as far as necessary for that demonstration objective.

1.2 Basin Selection

The Salt River Basin was selected as a demonstration site because it was within the Mississippi Model system, NEXRAD data were available, and the St. Louis District water control staff had a strong interest in improving forecasts of inflow to the Mark Twain Lake for flood control operations. Coordination with the District staff resulted in a planned cooperative model development using HEC and District staff. By memorandum of 21 April 1995, HEC submitted the proposed project to the St. Louis District, and it was adopted.

1.3 Basin Description

The Salt River Basin is located in northeastern Missouri. The basin drains an area of 7304 km^2 (2820 mi^2), discharging into the Mississippi River between Lock and Dams 22 and 24. Clarence Cannon Dam, impounding Mark Twain Lake, is located 101.4 km (63.0 mi) upstream from the confluence with the Mississippi River. A re-regulation dam exists at a distance 86.1 km (53.5 mi) upstream from the outlet. A total of 6048 km^2 (2335 mi^2) drain into Mark Twain Lake. Figure 1 shows the location of the Salt River Basin.

1.4 Acknowledgments

This study was performed by Daniel Kull. Troy Nicolini provided study guidance and management. John Peters and Arlen Feldman provided additional guidance and management.

Thomas Evans provided guidance for Arc/Info GIS related tasks. Raymond Kopsky and Jule Bartels of the St. Louis District provided valuable assistance in supplying information and assembling data.

Figure 1
Salt River Basin Location

Chapter 2

Development of the HEC-1 Model

2.1 Model Development Approach

The methodology by which real-time forecasting models are developed follows four steps: calibration of parameters from historical events, adoption of parameters, verification of adopted parameters, and parameter adjustment in operational forecast mode. Ideally, these steps would have been carried out for estimation of modClark parameters using radar rainfall events as input to a modClark model. However, radar rainfall data is available only since 1995. Therefore, the calibration of parameters was performed using historical gaged events in 1991-95 for the HEC-1 model (USACE 1990), with the assumption that the results would be acceptable estimates of parameters for use with modClark. Three other events in 1995 were then used to verify and adjust the HEC-1 parameters for use with the modClark procedure. This was only a preliminary calibration; more events should be used for a complete calibration for use as an operational model. Also, adjustments to these parameters in operational forecast mode would need to be performed.

2.2 Calibration Data

2.2.1 Acquisition

Hydrometeorological data were obtained from the District in HEC-DSS (USACE 1994) format for October, 1983 until the present. The data included rainfall and streamflow for locations within the basin, as well as for locations which were both near the Salt River Basin and within the St. Louis District. Rainfall data for gages near the Salt River Basin but outside the District were also sought. This was needed for calibration of basin parameters, as well as for comparison of gaged rainfall and radar rainfall measurements. Three sources of rainfall were investigated: The National Climatic Data Center (NCDC), the Kansas City District (west and south of basin), and the Rock Island District (north of basin). Time restrictions prohibited obtaining data from NCDC and the Kansas City District had no hourly rainfall data available for the study area. The Rock Island District provided hourly rainfall for six gages within the vicinity of the study area. In total, 22 rainfall gages were used: ten within the Salt River Basin, six outside the Basin in the St. Louis District, and six outside the basin in the Rock Island District. The final rain gage network was fair, with an area of poor coverage west, northwest, and southwest of the basin. None of the NCDC rain gages would have alleviated this problem.

2.2.2 Correction

Preliminary data checking and correction were performed on the appropriate rainfall and flow data provided by the St. Louis District. The data included cumulative and incremental hourly rainfall. The incremental rainfall was apparently produced from cumulative data which contained errors. Therefore, the data correction was performed on the original cumulative rainfall, and then incremental rainfall was generated using DSSMATH (USACE 1994). DATCHK and DATVUE (USACE 1995a) were used to aid in data error detection and correction. The associated data checking files will be provided to the District so that they can be further refined and included in the final real-time forecasting capability.

2.3 Subbasin Definition

For the purposes of this study, the Salt River watershed was subdivided into 14 subbasins (Figure 2). Eleven of these are located upstream of Clarence Cannon Dam. Of the 14 basins, nine are gaged (Figure 3); also shown on Figure 3 are the next generation radar rainfall (NEXRAD) cells for the Salt River Basin. The Long Branch (LBSF) subbasin has a relatively new gage with no historical records before 1995. It was thus treated as an ungaged headwater subbasin during parameter calibration. Two other subbasins, Otter and Black Creeks, are also ungaged headwaters. The remaining three ungaged subbasins are the local areas contributing runoff to Mark Twain Lake, the re-regulation pool, and the Salt River outlet at Ashburn. Gage locations for these subbasins are included in Figure 3 as SAMT, SANB, and SAAS respectively, as important water control data locations.

2.4 Clark's Parameters Estimation

2.4.1 Historical Calibration

Clark's Unit Hydrograph and loss rate parameters were needed for the HEC-1 model. Historical events were analyzed for the eight gaged subbasins. Eight events were chosen based on magnitude and hydrograph isolation. These events, including the simulation and optimization windows used for parameter optimization, are given in Table 1 (exact hours are in parentheses). As an example of relative event magnitude, Table 1 shows the peak flow rate of the North Fork Salt at Shelbina gage (NFSH). The optimization window is used to ensure that the parameter calibration is focused on the principal event hydrograph. Some of these optimization windows were changed depending on specific subbasin rainfall responses; the listed windows are given for general reference.

The PRECIP program (USACE 1989) was used to generate basin average precipitation for each of the calibration events. The program utilized all available gaged rainfall data, including data from gages outside of the Salt River Basin. Basin-averaged precipitation records are given a HEC-DSS record F-part of AVE. The associated gage information files will be

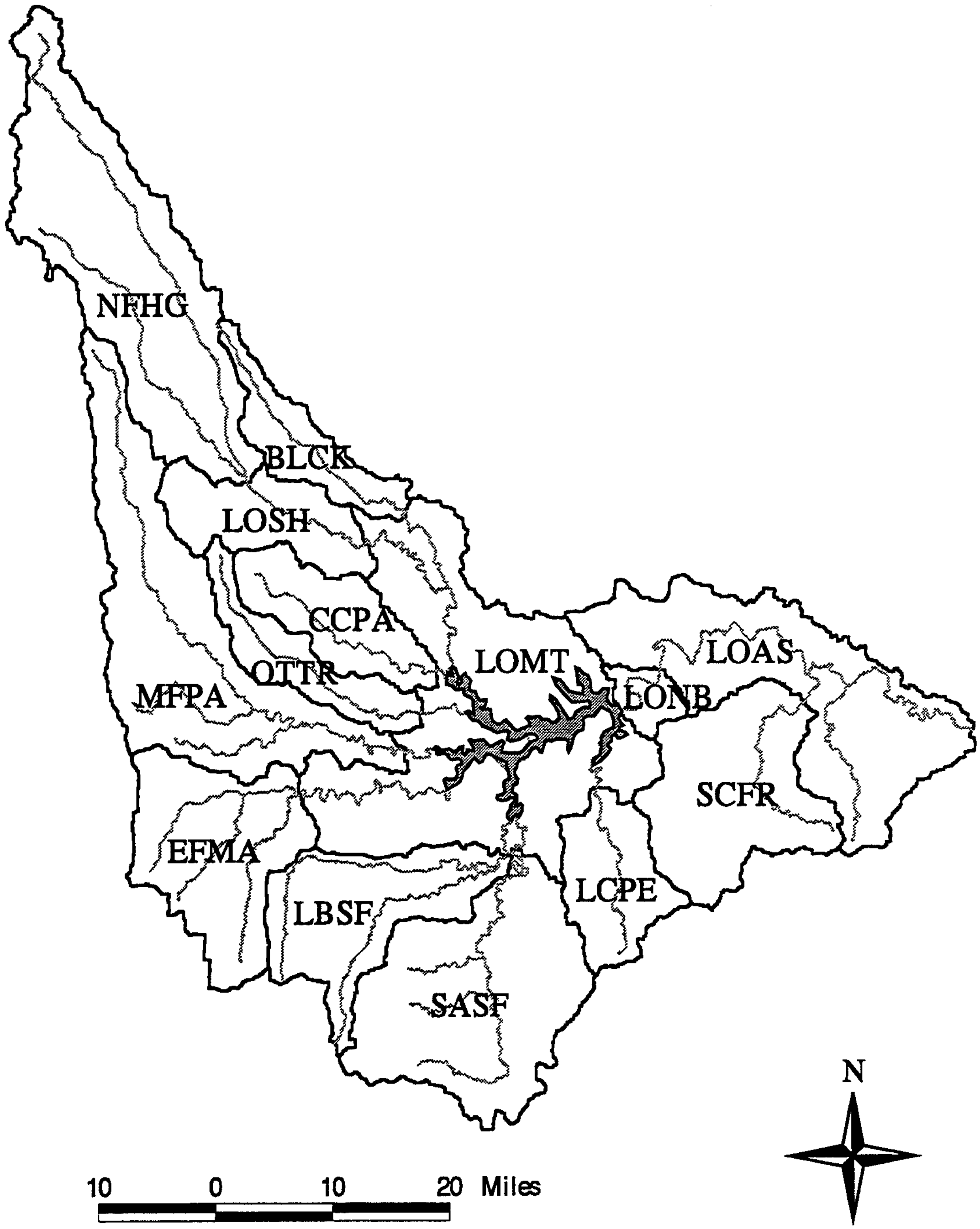

Figure 2
Salt River Subbasins and Mark Twain Lake

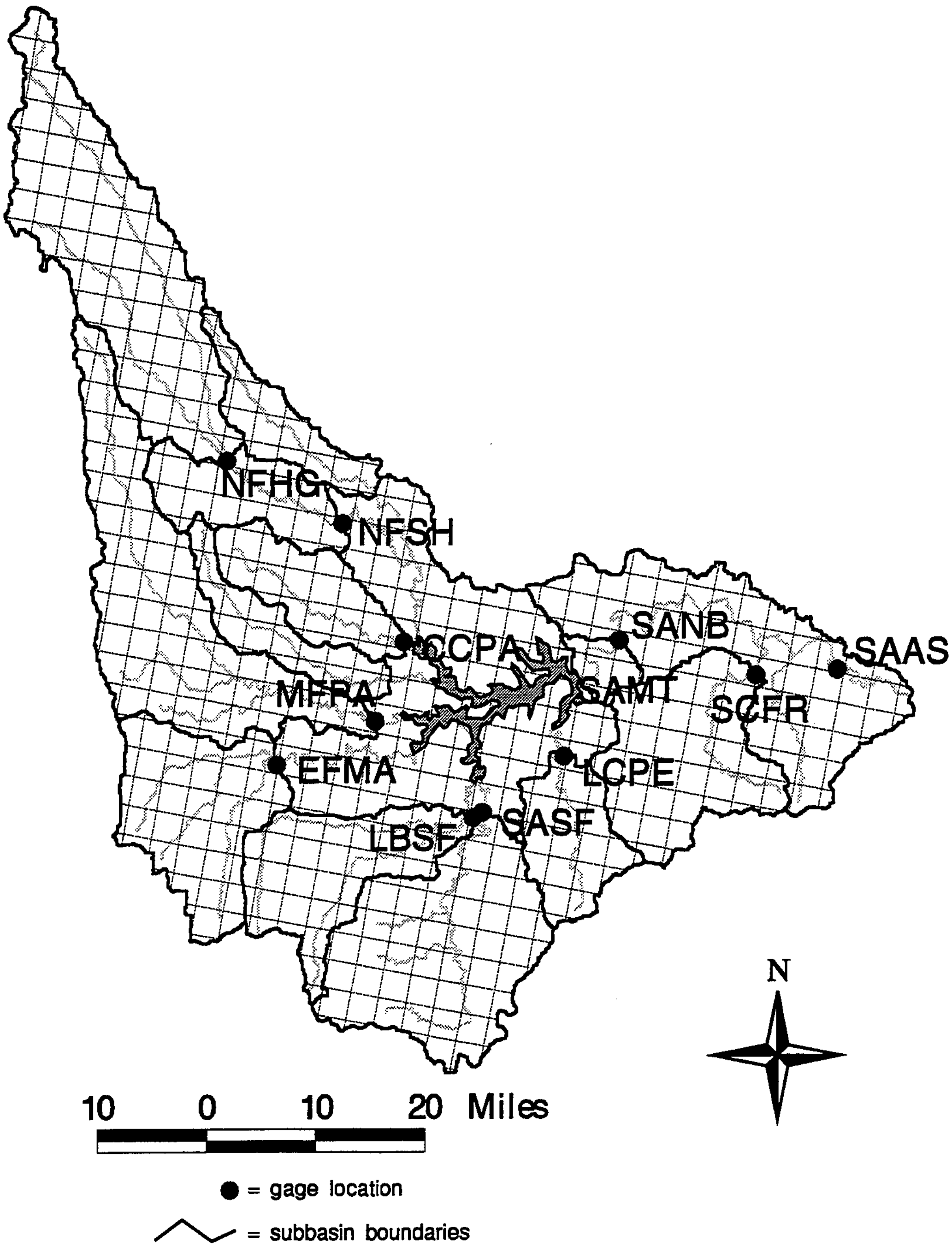

Figure 3
Salt River Basin Gage Locations, Subbasins, and NEXRAD Cells

Table 1
Events used for Rainfall-Runoff and Loss-Rate Parameter Estimation

Event	Peak Flow at NFSH m^3/s (cfs)	Simulation Window	Optimization Window
1	402 (14200)	9/21 (0100) - 10/13 (2400), 1986	9/28 (0100) - 10/7 (2400)
2	178 (6300)	7/9 (0100) - 7/18 (2400), 1991	7/11 (0100) - 7/14 (2400)
3	416 (14700)	6/30 (0700) - 7/6 (1500), 1993	6/30 (1900) - 7/3 (2300)
4	201 (7100)	7/6 (1600) - 7/10 (2400), 1993	7/7 (1100) - 7/9 (2200)
5	181 (6400)	9/19 (0100) - 9/28 (2400), 1993	9/22 (0600) - 9/25 (0300)
6	98 (3450)	4/8 (0100) - 4/20 (2400), 1994	4/10 (1200) - 4/14 (0600)
7	311 (11000)	5/12 (0100) - 5/23 (0900), 1995	5/16 (1100) - 5/20 (1900)
8	269 (9500)	5/23 (1000) - 6/3 (2400), 1995	5/23 (1000) - 5/26 (1000)

provided to the District so that they can be further refined and included in the final real-time forecasting capability.

The HEC-1 automatic optimization feature was applied to the eight gaged subbasins for all eight events. Event one proved to be unusable for all subbasins. Also, the gage on Crooked Creek near Paris (CCPA) yielded unusable results for all events. This may be due to the influence of Mark Twain Lake backwater on the flow gage. The results of the automatic calibration were analyzed to obtain values for the Clark time of concentration (T_C), the Clark storage attenuation coefficient (R), and the initial (STRTL) and constant (CNSTL) loss-rates. The adopted values for T_C and R are given in Table 2. The loss rates were checked for general physical sense, but not calibrated in detail. The task of developing loss-rate zones and determining values for the zones for real-time applications is left to more detailed flood forecast project studies.

2.4.2 Parameter Regionalization

To develop estimates for T_C and R for the ungaged basins, a regional analysis was performed on the above estimated Clark's parameters. As is often the case, $R/(T_C + R)$ was relatively constant for the subbasins, and the following value was adopted:

$$\frac{R}{T_C + R} = 0.44 \tag{1}$$

Table 2
Rainfall-Runoff Parameters Adopted for Gaged Subbasins

Subbasin	Area km^2 (mi^2)	Length km (mi)	T_C (hr)	R (hr)
North Fork Salt at Hagers Grove (NFHG)	922.6 (356.2)	94.3 (58.6)	23	18
North Fork Salt near Shelbina (NFSH)	1204.9 (465.2)	118.4 (73.6)	37	31
Middle Fork Salt at Paris (MFPA)	865.8 (334.3)	105.2 (65.4)	74	15
Elk Fork Salt near Madison (EFMA)	516.7 (199.5)	35.4 (22.0)	31	9.5
South Fork Salt above Santa Fe (SASF)	780.9 (301.5)	61.2 (38.0)	22	17
Lick Creek at Perry (LCPE)	271.4 (104.8)	31.4 (19.5)	12	8
Spencer Creek near Frankford (SCFR)	536.1 (207.0)	45.7 (28.4)	12.5	10

A regression of T_C and R with the physical basin characteristics of area (A), watercourse length (L), and slope (S) was performed. The slope was defined in feet per mile between points 10% and 85% from the subbasin outlet along the main channel. Various linear and exponential combinations of A, L, and S were tried with either T_C, R, or T_C and R. Most yielded standard errors (S_e) and coefficients of determination (R^2) of similar magnitudes. Equation (2), with R^2=0.68 and S_e=0.37, was chosen based on its use of only two variables, and that it was sufficient for the demonstrative objective of this study.

$$T_C + R = 0.88\, A^{0.338}\, L^{0.535} \quad (2)$$

With only seven data points in the regression, the use of fewer variables was driven by the principle of parsimony. In addition, there was limited confidence in the slopes manually measured from USGS 1:250,00 scale topographic quads. Equations (1) and (2) were then used to estimate the Clark's parameters for all ungaged basins. The results are given in Table 3.

Table 3
Rainfall-Runoff Parameters Estimated from Regional Analysis

Subbasin	Area km^2 (mi^2)	Length km (mi)	T_C (hr)	R (hr)
Black Creek at Rt. 15 Crossing (BLCK)	209.3 (80.8)	48.3 (30.0)	13.1	10.3
North Fork Salt near Shelbina - local (LOSH)	282.3 (109.0)	24.1 (15.0)	10.0	7.9
Crooked Creek near Paris (CCPA)	280.8 (108.4)	29.0 (18.0)	11.0	8.6
Otter Creek at road crossing (OTTR)	217.3 (83.9)	30.6 (19.0)	10.4	8.2
Long Branch above Santa Fe (LBSF)	449.4 (173.5)	36.7 (22.8)	14.6	11.5
Mark Twain Lake local inflow (LOMT)	1098.2 (424.0)	35.4 (22.0)	10.0	7.9
Salt River at Norton's Bridge - local (LONB)	71.5 (27.6)	18.0 (11.2)	5.4	4.2
Salt River at Ashburn - local (LOAS)	801.6 (309.5)	83.4 (51.8)	27.6	21.7

2.5 Routing Parameter Estimation

To determine the Muskingum routing parameters for the basin, historical flows on the North Fork from Hager's Grove to Shelbina were analyzed. A manual calibration yielded the best routing parameter values as: K=26 hr, x=0.1, and n=8 steps. All other routing parameters within the basin were determined by prorating the above K value according to reach length and using x=0.1. Of the 14 routing reaches in the model, nine cover relatively short distances from gaged headwater subbasins to the reservoir. Due to the variability of the reservoir extent, these may be unnecessary.

2.6 Calibration and Model Review

The calibration and regression performed for this model development were not exhaustive analyses. In particular, the regionalization of parameters was performed at a less detailed level than is normal for full watershed model development. With the primary goal of this study being the demonstration of the weather radar - HEC-1 modClark methodology and program, less emphasis was placed on the model parameter derivations. In addition, budgetary and time constraints limited the modeling effort.

A schematic of the HEC-1 model is given in Figure 4. To account for the precipitation falling directly on Mark Twain Lake, the reservoir surface area of 152.8 km^2 (59 mi^2) (USACE 1991) was considered to be impermeable. Taken as part of the local contributing area to the lake, this turned out to be 152.8/1098.2 km^2/km^2 (59/424 mi^2/mi^2), or 12.2 % imperviousness for the Mark Twain Lake local (LOMT) subbasin. All output from the basin-averaged rainfall HEC-1 model is stored in HEC-DSS with F=COMP.

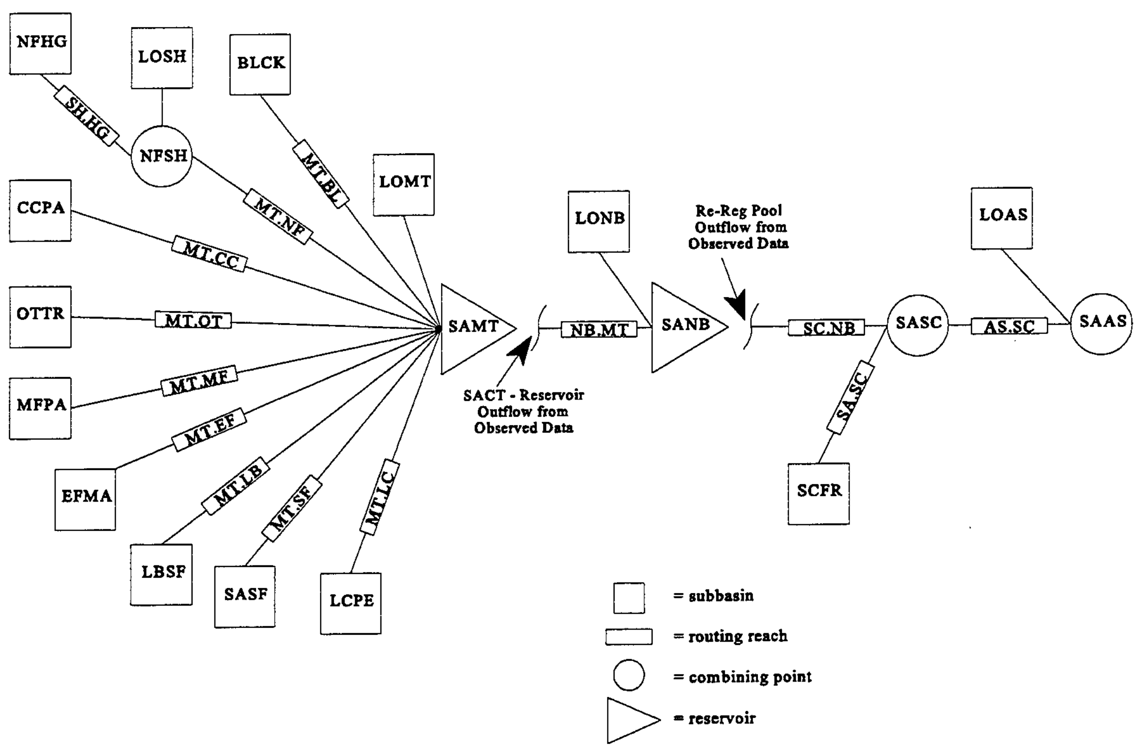

Figure 4
Salt River Basin Model Schematic

Chapter 3

Development of the modClark Model

3.1 modClark Methodology

HEC has developed the computer program modClark to utilize some of the now available spatially distributed watershed and rainfall information in a real-time application. It cannot be considered as a final method for the integration of areally oriented data into real-time hydrologic forecasting; rather, it is a first step towards a complete union of the two. With this in mind, modClark was designed to work with existing watershed models so as to "ease" into the use of these new technologies and not force the drastic alteration of current watershed representations. The methodology uses two different types of digital spatially distributed data: digital elevation models (DEM), and Next Generation Weather Surveillance Radar (NEXRAD). An overview of the NEXRAD system is given in Appendix B.

The methodology used in modClark is an adaptation of Clark's Unit Hydrograph technique (Clark 1945) to accommodate spatially distributed rainfall data (USACE 1995d). The code was developed in order to work with the computer programs HEC-1 and HEC-1F. Before the program can be used, pre-processing to obtain appropriate input data must be performed. A digital elevation model (DEM) for the watershed in question must first be obtained from the USGS. The travel distance from each DEM cell to the basin outlet is then determined via GIS processing. These 90 m (295 ft) cells are then registered and aggregated into the 4 km (2.49 mi) HRAP cells used for NEXRAD (HRAP is briefly reviewed in Appendix B). The average travel length from each HRAP cell to the outlet is then found. The Clark time of concentration, T_C, and storage attenuation coefficient, R, for the entire watershed are obtained from previous studies or through established calibration methods. (In this pilot application, a simple regional analysis was used.) This process needs only be performed once, unless the basin itself is drastically changed.

These data, along with infiltration and baseflow variables, are then utilized by modClark. Travel time from each cell is calculated by prorating the basin time of concentration:

$$[\text{travel time}]_{\text{cell}} = T_C \frac{[\text{travel length}]_{\text{cell}}}{\text{maximum of the cell travel lengths}} \tag{3}$$

The spatial processing in modClark is now utilized with the application of NEXRAD rainfall data to each cell. The methodology is shown in Figure 5. The rainfall excess is computed for each cell using the general watershed data. Rainfall excess at each cell is lagged to the basin outlet according to the cell's travel time. Next, individual lagged cell outflows are routed

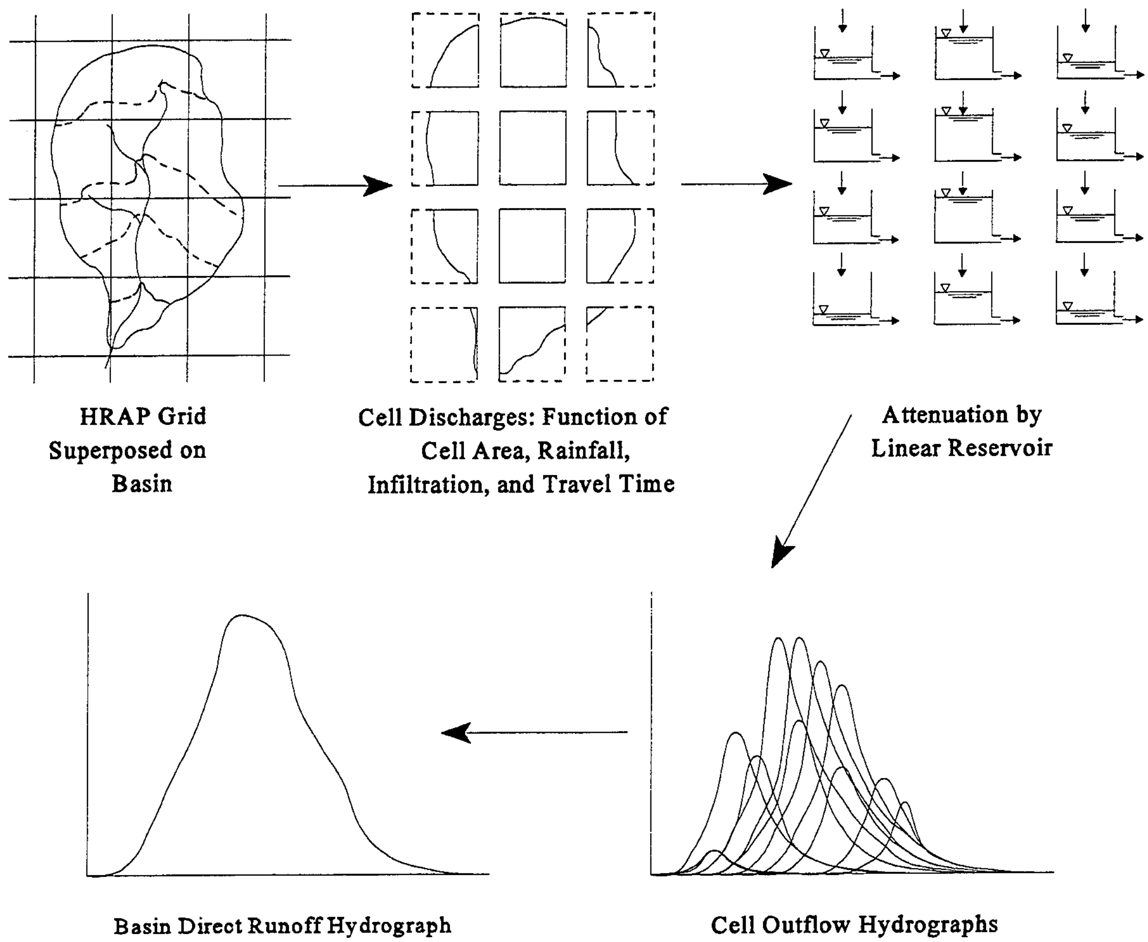

Figure 5
modClark Direct Runoff Methodology

through a linear reservoir using R. The routing is identical to that used in Clark's original methodology. The lagged and routed outflows are then summed, baseflow is added, and the watershed's outlet hydrograph is produced.

3.2 modClark River Basin Analysis Procedure

A basin-wide modClark model consists of several different components. Before any analysis can be performed, a variety of input files need to be generated. DEM and HRAP cell area and distance calculations are performed by software named GridParm-DEM2HRAP (USACE 1995b). This software consists of a set of macros run on the Arc/Info GIS, using USGS DEMs and user specified subbasin outlet locations to produce a grid-cell characteristic file ready for use with modClark. The file contains for each subbasin a list of the HRAP grid-cells with

their x and y coordinates, area, and average travel length to the subbasin outlet. Two other input files are needed for a basin-wide modClark analysis. A basin characteristics file supplies modClark with the rainfall-runoff parameters necessary for hydrograph development. A file for use with HEC-1 or HEC-1F contains routing and combining data in order to calculate flows throughout the river basin. These files are reviewed in greater detail in sections 3.3 - 3.5.

NEXRAD rainfall data is downloaded from the distribution site and stored in HEC-DSS. Using the HRAP cell characteristic file, the subbasin characteristic file, and the NEXRAD rainfall data, modClark calculates subbasin outflow hydrographs. These subbasin hydrographs are stored in HEC-DSS. HEC-1 or HEC-1F then reads the modClark generated subbasin hydrographs, and using the routing and combining data file, calculates basin-wide flows. These flows are again stored in HEC-DSS. Figure 6 shows a flow chart for the modClark river basin analysis procedure.

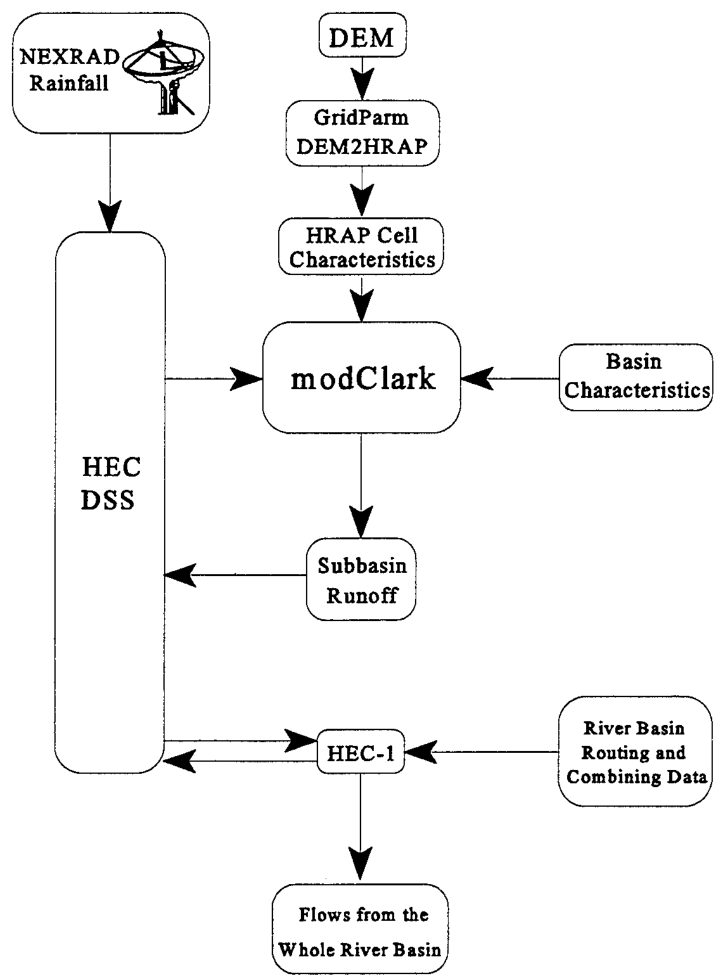

Figure 6
modClark River Basin Analysis Procedure

3.3 HRAP Cell Characteristic File

To develop the grid-cell characteristic file, the GridParm-DEM2HRAP (USACE 1995b) procedure was performed using the Arc/Info GIS. Three USGS Digital Elevation Model (DEM) quads covered the basin: Centerville-east, Moberly-east, and Quincy-west. These were downloaded from the USGS EROS Data Center through a file transfer protocol (ftp). Figure 7 shows the Salt River Basin DEM. The GridParm-DEM2HRAP procedure requires a three letter basin-specific prefix to name all generated files. "sal" was used for the Salt River Basin. After the DEM's were downloaded, the "demload" routine was used to convert the files to a usable Arc/Info format. This routine also removes pits and delineates streams. A text file containing the 14 subbasin outlet points (gage locations when possible) was then created. This was used with the "demwsh" routine to delineate subbasins. Finally, the "parmhrap" routine was run. This aggregates the 90 m. DEM grid-cells into the 4 km. HRAP (NEXRAD) grid-cells. It also calculates the area and average travel distance to subbasin outlet for each HRAP cell. Figure 3 showed the gage locations, subbasins, and HRAP grid-cell delineations for the Salt River Basin. The grid-cell characteristic file named "salcells" was automatically produced by the GridParm-DEM2HRAP procedure.

3.4 Basin Characteristics File

The basin characteristics file is of the same format as the standard HEC-1 input file. It contains for each subbasin: total subbasin area, Clark's unit hydrograph parameters, loss rate parameters, and base flow parameters. Initially, all the above listed parameters were kept the same as those used in the original HEC-1 model. Loss rates were later changed per modeled event, as is described in section 4.2. The hydrologic parameter data file also specifies the pathnames for storage of generated flow hydrographs. For all modClark output, the A, B, C, D, and E pathnames are the same as those generated by HEC-1. The F part is set to "MODCLARK".

3.5 Routing and Combining File

The final input file, used with HEC-1, reads HEC-DSS stored modClark subbasin runoff and routes and combines it to produce basin-wide flows. It differs from the original HEC-1 input file only in that the subbasin runoff is read from HEC-DSS instead of calculated with HEC-1. Again, all output from this is labeled with F=MODCLARK in HEC-DSS.

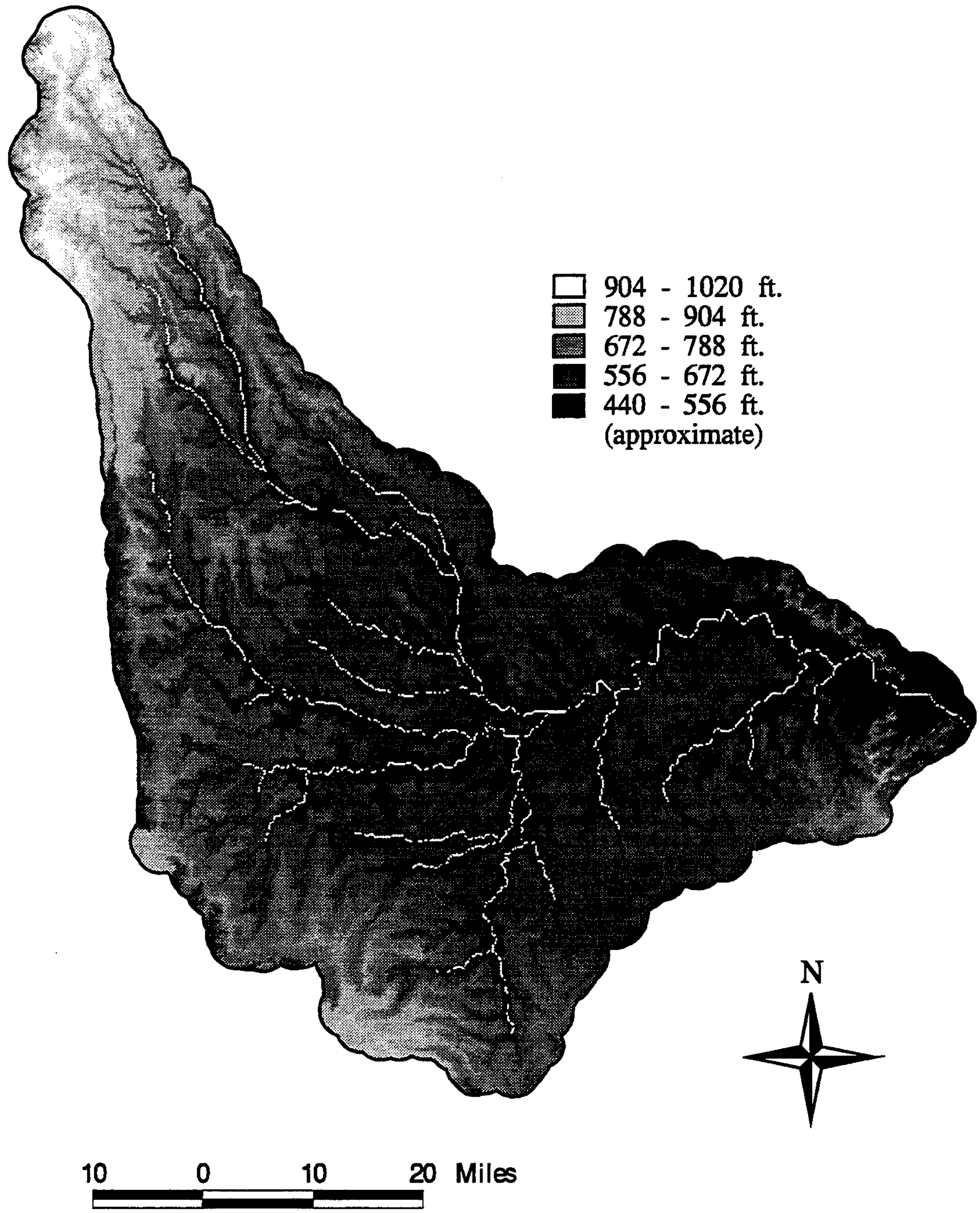

Figure 7
Salt River Basin DEM with DEM Derived Stream Delineations

Chapter 4

Verification and Adjustment of Models for 1995 Events

4.1 Data Acquisition and Management

The PRECIP program was utilized to estimate basin-averaged gaged precipitation for comparison with the radar precipitation. The PRECIP input file was developed to use the gages supplied by both the St. Louis and Rock Island Districts. However, if PRECIP finds no data for a gage, it will ignore that gage for the particular event (or time interval) and use the next closest gage. This allows the use of many rain gages without changing the PRECIP input file.

Stage I radar data, which is raw data that has not been ground-truthed to rain gages, was the only form of NEXRAD data available form the St. Louis (LSX) site. Appendix B gives an overview of the NEXRAD system and its current level of development. The Stage I radar data for 1995 was loaded into HEC-DSS from the St. Louis District files. This data from the St. Louis radar does not cover the entire Salt River Basin. 16 of the 84 HRAP cells (about 19%) composing the North Fork at Hager's Grove subbasin are out of the sweep area. For this study, those 16 cells were considered to have no radar rainfall. (Stage III radar data, if available, would have mosaicked the data from neighboring radar sites, yielding full basin coverage.) The data was converted to HEC-DSS format and adjustments made for time-shifts.

Radar data comes in UTC - Coordinated Universal Time. Existing software could not conveniently change the radar data from UTC to local time. The gaged data from the District is in Central Time (daylight savings for appropriate summer times). Through DSSMATH, the gaged precipitation and streamflow data was shifted 5 or 6 hours forward in time, depending on the time of year, to account for the difference and make comparisons easier. This shifted data includes the term "UTC" in its HEC-DSS record F part (i.e. F=UTC-OBS, F=UTC-COMP, F=UTC-AVE, etc.).

4.2 Event Simulation

Three 1995 events were modeled with modClark. These events were also modeled with HEC-1 using basin-averaged gage rainfall. The events were: May 23 to May 31, July 3 to July 13, and July 24 to July 25. The May event was relatively uniform in its spatial rainfall distribution, while the two July events were markedly nonuniform. Table 4 shows the loss rates used in the simulations.

For the early July event, the loss-rates were adjusted globally for all subbasins to best model the derived Mark Twain Lake inflow volume. This reservoir inflow was computed by the

Table 4
Loss Rates used in Simulations

Date	Gage site	HEC-1 STRTL mm (in)	HEC-1 CNSTL mm (in)	modClark STRTL mm (in)	modClark CNSTL mm (in)
7/03-7/13	NFHG	3.8 (0.15)	1.3 (0.05)	30.5 (1.2)	7.6 (0.3)
7/03-7/13	SAMT	3.8 (0.15)	1.3 (0.05)	30.5 (1.2)	7.6 (0.3)
7/24-7/25	SCFR	30.5 (1.2)	20.3 (0.8)	45.7 (1.8)	25.4 (1.0)
5/23-5/31	LCPE	20.3 (0.8)	3.8 (0.15)	0	0
5/23-5/31	SCFR	15.2 (0.6)	3.8 (0.05)	0	0

St. Louis District from outflow and storage relationships. Figure 8 shows the gaged rainfall isohyets for July 4th from 0600 to 0700 (all spatial rainfall plots presented in this section are in millimeters, whereas the rainfall shown and used with the associated simulation models is in inches). Spatial rainfield plots were developed with the WCDS-SVT (Water Control Data System - Spatial Visualization Tool) program, which is currently under development. For the gage-measured rainfield plots, the interpolation method used to develop isohyets needed to extrapolate data for the entire area within the plot boundaries. As a result, areas outside the vicinity of the gages often have irregularities in the plot, as can be seen in Figure 8.

For this early July event, the gage network did not record high intensity rainfall anywhere in the Salt River Basin. Figure 9 shows the resultant HEC-1 basin-averaged rainfall simulation for the North Fork at Hager's Grove (NFHG). Even with minimal loss rates, the model underestimates the flow. Figure 10 shows the radar measured rainfall for the same hour. An area of intense rainfall is present over the NFHG subbasin. The associated modClark simulation produces a flow volume and peak of similar magnitude to the observed values (Figure 11). With the sparse gage network around the NFHG subbasin, the basin-averaged rainfall simulation model did not capture this locally intense rainfall activity. It should be kept in mind that about 19% of the NFHG subbasin did not receive any radar rainfall because it was outside of the scan limits. Figure 12 shows the Mark Twain Lake inflows for the same event. Although the volume of the basin-averaged rainfall simulation can be made similar to the observed volume, the shape cannot be matched through loss rate adjustment. The additional volume, which is not seen in the North Fork flows (Figure 9), comes from the overestimation of flows in other subbasins. The modClark method is better able to model the spatially distributed nature of this particular event.

The late July event was locally intense, concentrated over Spencer Creek (SCFR). Figures 13 and 14 show the gaged and radar measured rainfall for July 24th from 2300 to 2400. The rain gage network, which is more concentrated in this part of the Salt River Basin, was able

to account for the local rainfall. Figure 15 shows the resultant basin-averaged rainfall and modClark simulation results. Few conclusions can be drawn from these results. Note that this was a small magnitude event, whereas the basin rainfall-runoff parameters were calibrated with large magnitude storms.

The May event was more spatially homogeneous than the two July events. Figures 16 and 17 show the gaged and radar measured rainfall for May 23rd from 0300 to 0400. Loss rates were adjusted separately for each subbasin. Figures 18 and 19 show the simulation results for Lick (LCPE) and Spencer (SCFR) Creeks. These two subbasins are shown as representative examples of all subbasin results. It can be seen that even with zero loss rates, the radar recorded rainfall does not produce enough runoff volume. Meanwhile, with reasonable loss rates, the rain gage network performed satisfactorily. The network is well concentrated in this eastern portion of the Salt River Basin, allowing it to reasonably measure rainfall events in that area. It appears that the raw (Stage I) radar data is inadequate for this event.

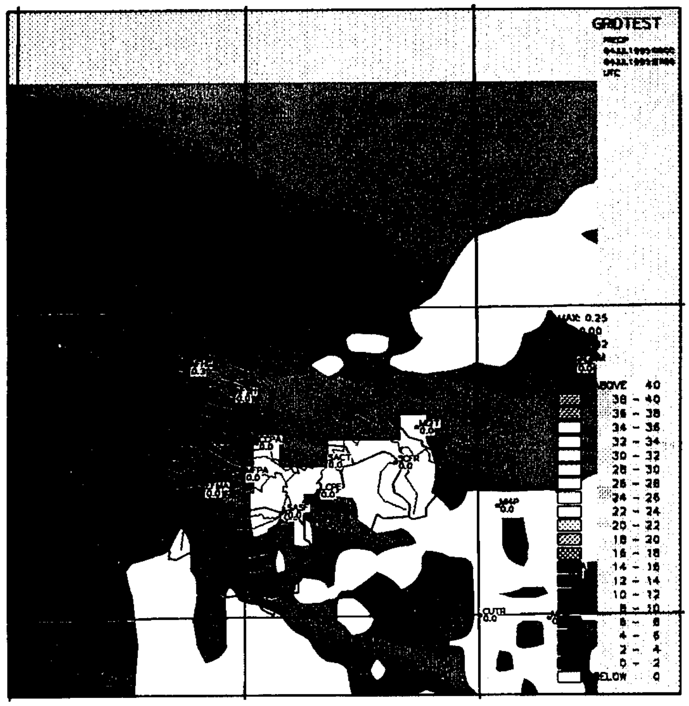

Figure 8
Gage Measured Rainfall for July 4, 0600-0700 UTC

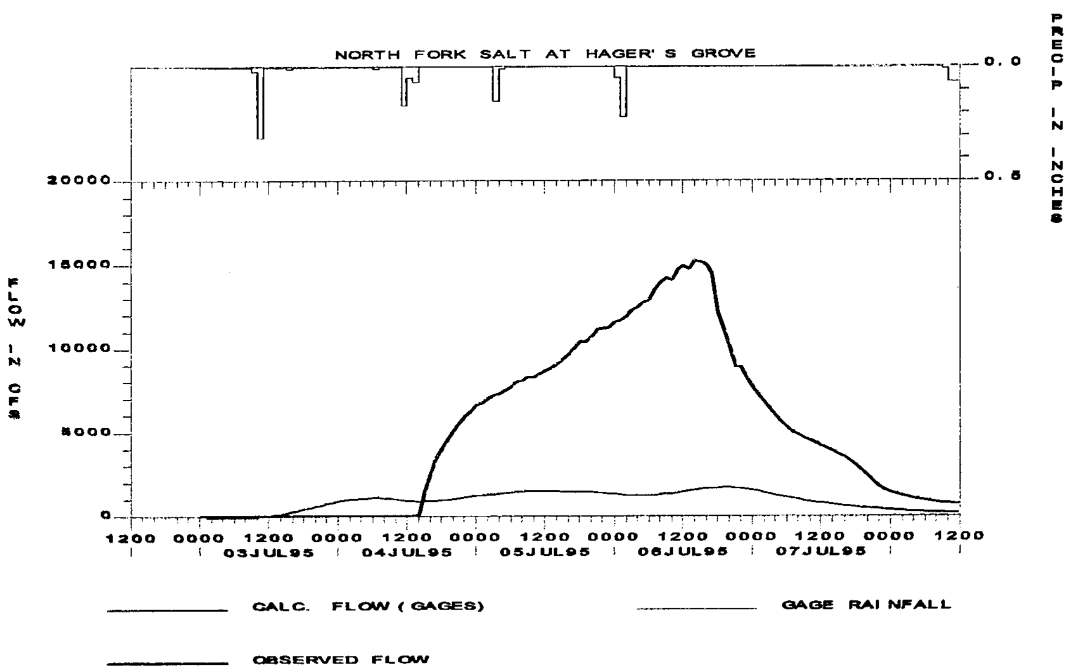

Figure 9
Basin-averaged Rainfall HEC-1 Simulation for North Fork Salt at Hager's Grove, July 3-8

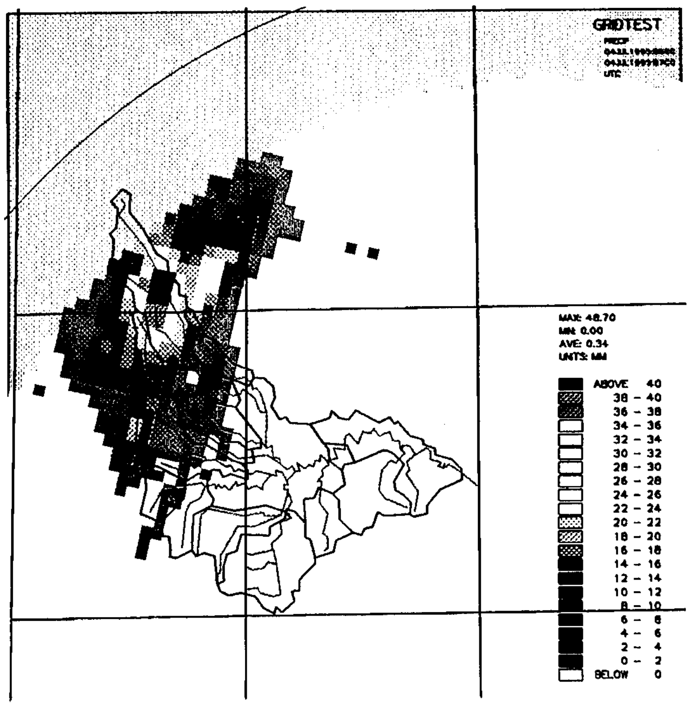

Figure 10
Radar Measured Rainfall for July 4, 0600-0700 UTC

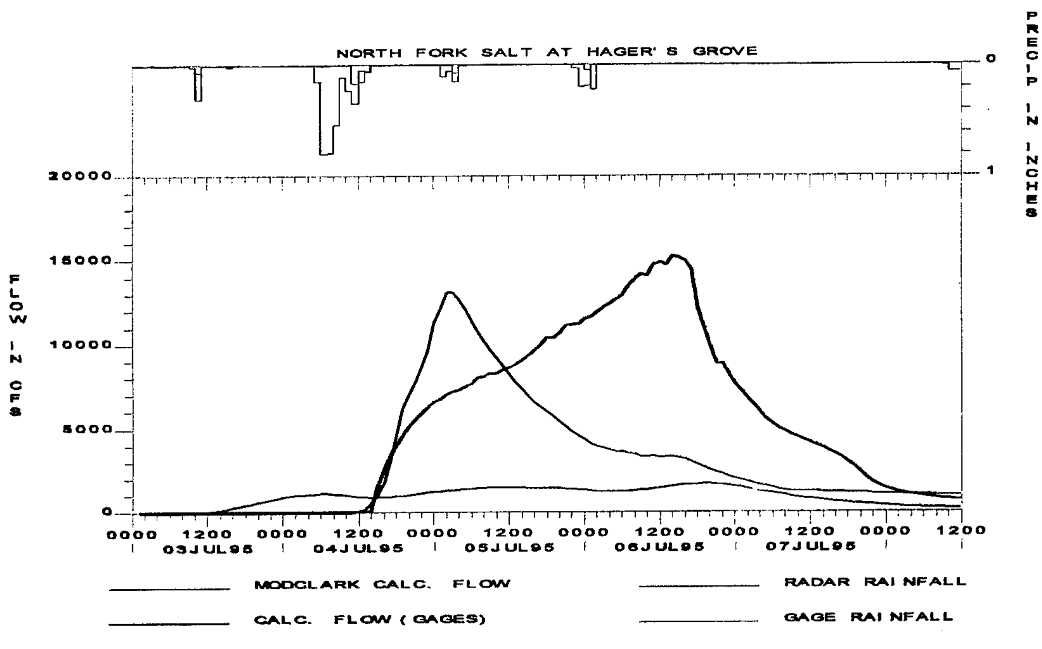

Figure 11
modClark Simulation for North Fork Salt at Hager's Grove, July 3-13

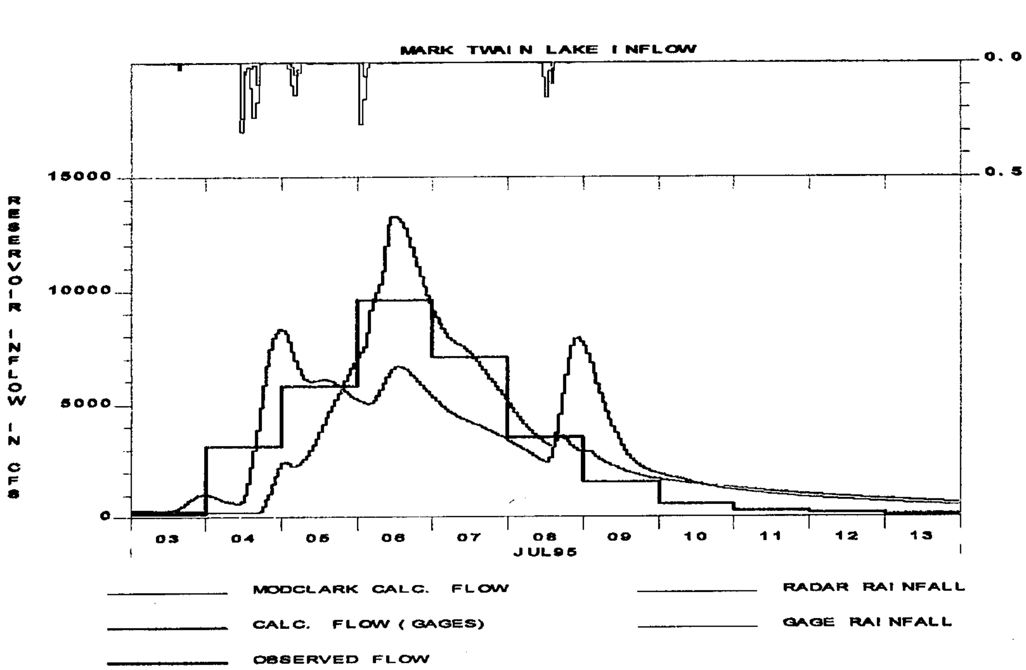

Figure 12
Simulations for Mark Twain Lake Inflow, July 3-13

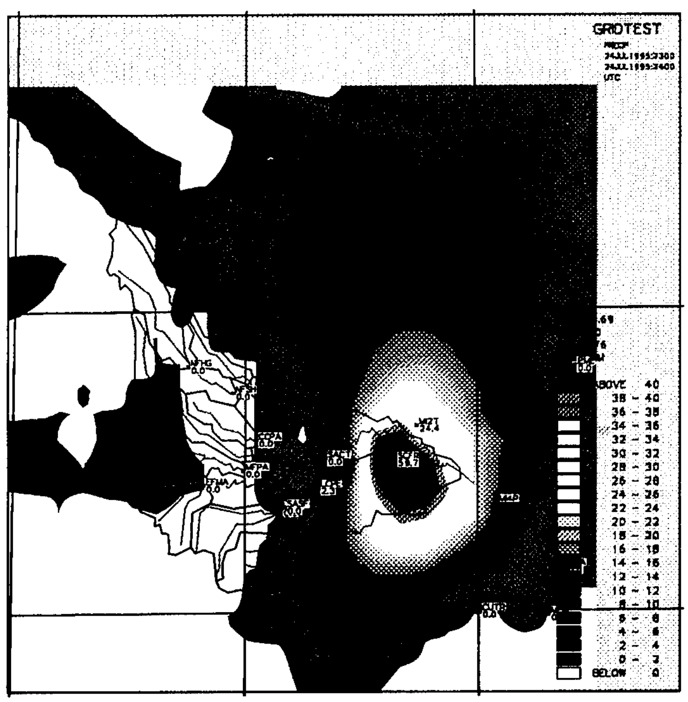

Figure 13
Gage Measured Rainfall for July 24, 2300-2400 UTC

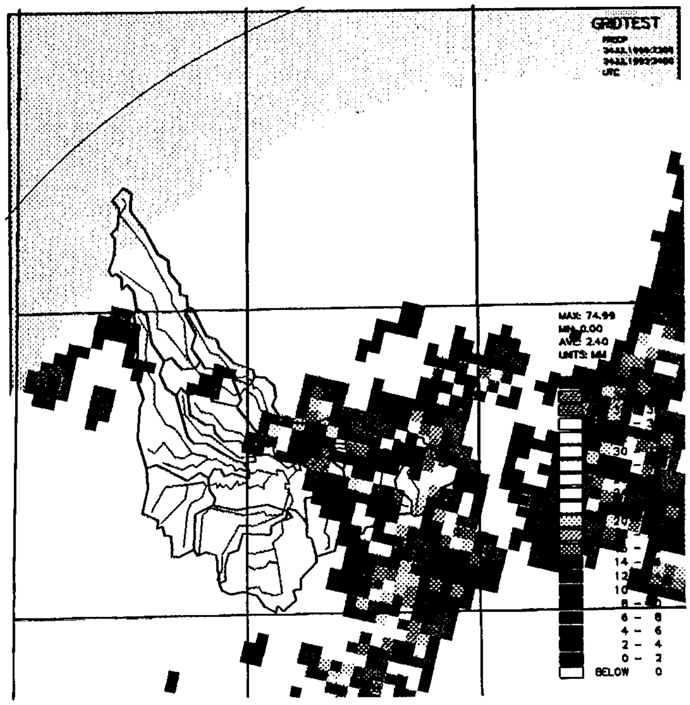

Figure 14
Radar Measured Rainfall for July 24, 2300-2400 UTC

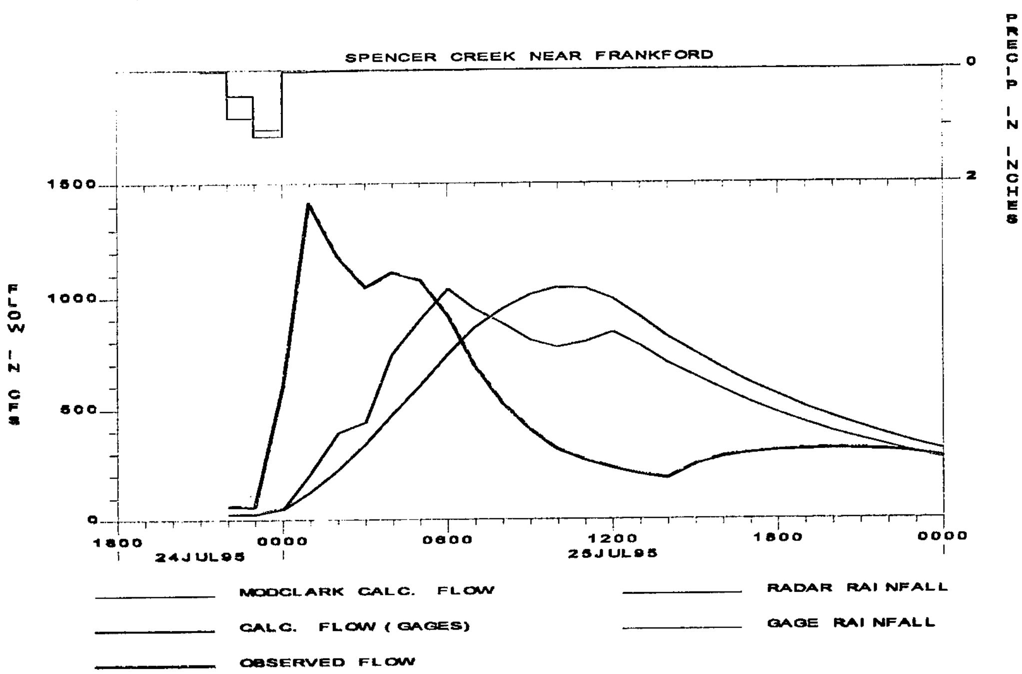

Figure 15
Simulations for Spencer Creek near Frankford, July 24-25

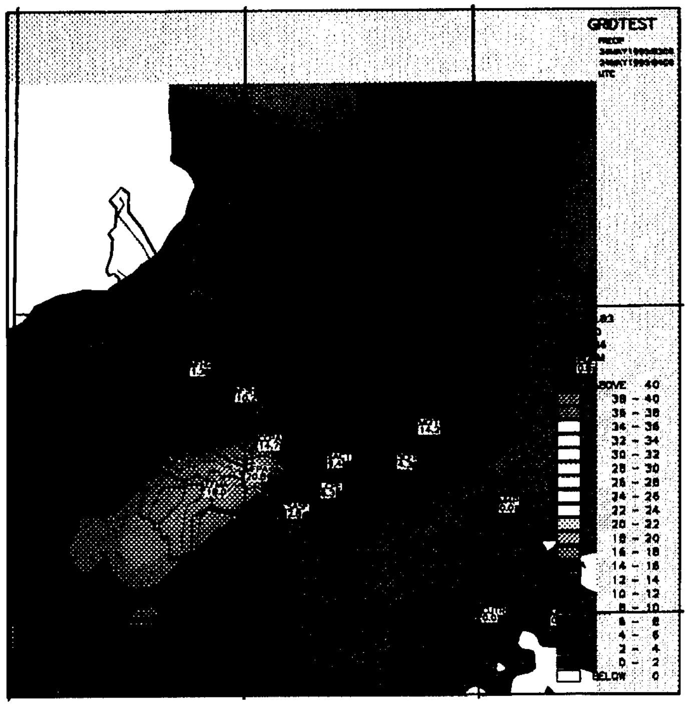

Figure 16
Gage Measured Rainfall for May 24, 0300-0400 UTC

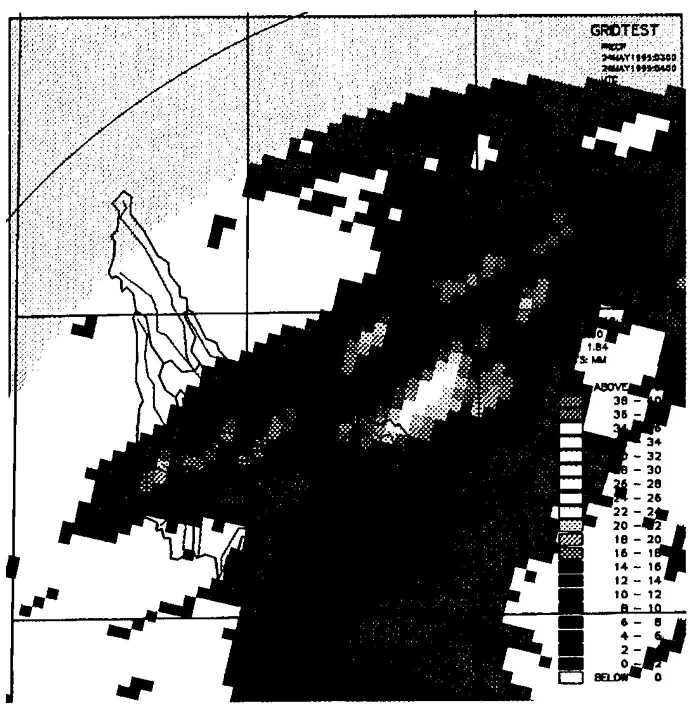

Figure 17
Radar Measured Rainfall for May 24, 0300-0400 UTC

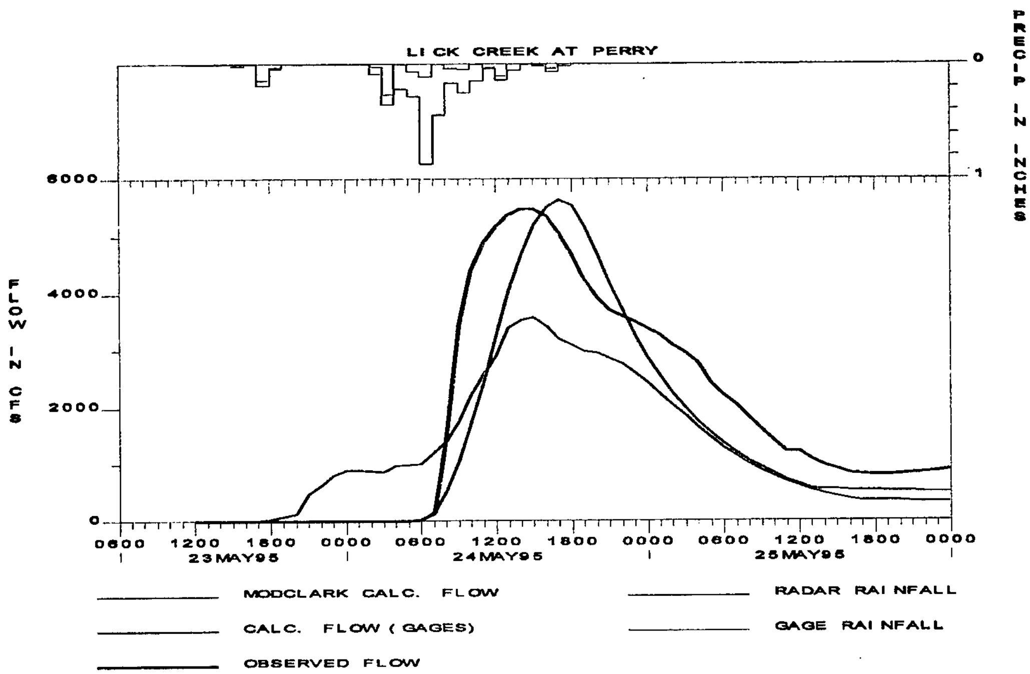

Figure 18
Simulations for Lick Creek at Perry, May 23-25

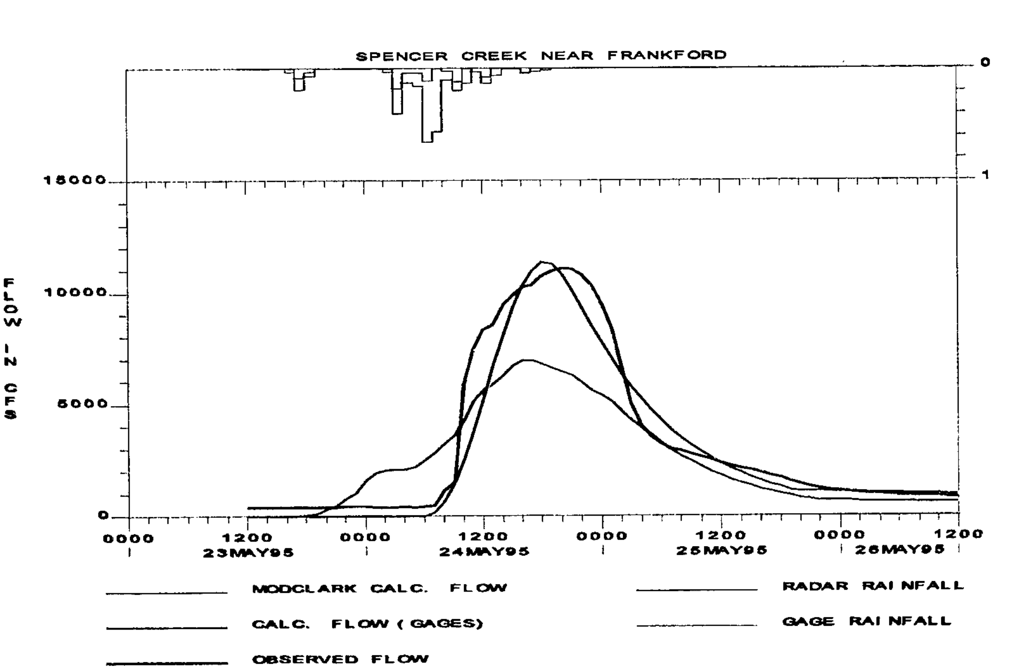

Figure 19
Simulations for Spencer Creek near Frankford, May 23-26

Chapter 5

Observations and Conclusions

5.1 modClark Model Development

The development of the modClark hydrologic parameter file is similar to the creation of an HEC-1 input file. The major difference between the construction of a modClark model verses a HEC-1 model is the generation of the grid-cell characteristic file. The GridParm-DEM2HRAP procedure makes this a relatively painless step, even to users with no Arc/Info experience. The seven steps of the procedure follow a logical development and the manual provides a detailed summary of what each step accomplishes. For the downloading of USGS DEM data (step 4), the use of a file transfer protocol (ftp) is presented such that the inexperienced Internet user will not have a problem. The only difficulty of the GridParm-DEM2HRAP procedure is one of patience, for some of the data processing steps can last a relatively long time (hours - depending on basin size). This procedure need only be performed once, unless a change in a subbasin outlet location is desired.

5.2 Model Performance

Use of radar rainfall for runoff estimation has the potential to make major improvements to the modeling of spatially varied rainfall events. The localized intensities of convective storms are often missed or not entirely captured by a rain gage network. Radar measurements provide for complete spatial coverage for the rainfield over a basin. Through modClark, these localized rainfall cells can be translated to runoff at the basin outlet. This tool is especially useful for areas with poor or non-existent rain gage coverage where the NEXRAD program has been implemented. The actual run-time for a modClark model is relatively small, depending on basin size, length of simulation, and traffic on the server. All simulations for the 7304 km^2 (2820 mi^2) Salt River Basin took less than one minute, including the ten day early July event. This fast simulation time is useful for real-time flood forecasting. An important aspect of the modClark process is the transferral of radar data to HEC-DSS format. For real-time applications, this must be automated.

5.3 Stage I Radar Data

Stage I radar data, as used in this study, does not undergo any corrective processing with rain gages. Although the radar is able to pick up the timing and location of rain cells, it can be markedly off in its absolute magnitude. A rain gage network provides point measurements at specific locations, the accuracy of which is a separate issue. The combination of these two systems, namely the ground-truthing of the radar data with gage measurements, would produce

improved rainfall representation for the entire basin. NEXRAD Stage II and III processing does this, utilizing a mean radar field bias based on a number of rain gages. Gage measurements are weighted more during spatially uniform events and less during well distributed storms (refer to Appendix B). For the purposes of a modClark simulation, Stage III data would offer a marked improvement. When modClark is run, it produces subbasin rain hyetographs. For further analysis, it would be interesting to compare these with those generated by PRECIP using gaged data.

Chapter 6

Implementation of modClark as a Real-Time Flood Forecasting Tool

At this point, only the basic Salt River Basin model, consisting of both the modClark and HEC-1 components, has been completed. As mentioned before, this pilot application was only intended to illustrate these new spatially distributed runoff capabilities. For the model to be implemented as a fully operational real-time flood forecasting tool, further work must be performed. This involves the development of files and procedures along two paths; those associated with traditional HEC-1F real-time flood forecasting methods, and those specific to new developments with modClark. This work is described below in the context of the various steps required for flow forecasting in the existing real-time water control system; new, but similar procedures are being developed in the current WCDS modernization effort (USACE 1995e).

For real-time flood forecasting, the modeled basin is divided into regional zones. Each zone contains subbasins with similar loss rate and base flow parameter values. This allows for faster parameter calibration during forecast operations. The defining of these zones and development of the BASNZONE file remains to be done for the Salt River Basin.

Flow and gage-measured precipitation are reported by the Data Collection Platforms (DCP) and stored in HEC-DSS. A requirement of real-time flood forecasting is that all data has been checked and necessary corrections made before the simulations are performed. DATCHK can be automatically implemented on a periodic basis, depending on the reporting patterns of the gages. DATVUE should be implemented at the water control manager's discretion, as a manual check of data quality and proper corrective analysis. Initial DATCHK and DATVUE input files were constructed during the original model development (section 2.2.2). These must be refined and verified in an operational mode before full implementation as an automatic function.

Before any real-time forecasting is performed, radar data for the simulation period must be downloaded and converted to HEC-DSS format. Radar data is retrieved from the PUPIE - Principle User Processor Interactive Emulator, located at the St. Louis District. The data is then converted into HEC-DSS format with the gridLoadStage1 program (USACE 1995c) and stored in the master database. Radar data is recorded in coordinated universal time (UTC) while DCP reported data is recorded in standard local time (section 4.1). To account for this, it is anticipated that modClark will be given the ability to shift data within its processing realm to local standard time. modClark output will thus be in local time, while the radar data will stay in UTC.

Real-time flood forecasting is performed with the aid of MODCON - Model Control, an interactive program which provides access to a series of real-time water control programs (USACE 1989). MODCON enables the user to perform the various analyses associated with real-time forecasting from a single input source. Pre-developed input files are required for many of these steps for efficient operational-mode forecasting. The JBAS - job control input file for executing batch jobs is necessary for running non-real-time water control programs from within the MODCON shell. A function character definitions file, GENFUN, enables single characters to represent a string of characters. This decreases the forecasting time by enabling faster manual inputs. Macros can be developed to initiate a series of MODCON input lines through a single input line. These macros are contained in the CONMAC file. JBAS, GENFUN, and CONMAC remain to be developed for the Salt River Basin.

The DATAST program generates a summary table of what data is available from the master database. This utilizes the DLIST input file. DLIST remains to be developed for the Salt River Basin.

Once the time-of-forecast has been set, the EXTRCT program is used to retrieve the required flow and radar data from the master database to a working HEC-DSS file (USACE 1989). The time window of retrieved data is a set period before the forecast time as defined in the EXTRCT input file EXTLIST. EXTLIST remains to be developed for the Salt River Basin.

The PRECIP program is used to compute subbasin-average precipitation based on gage measurements. Although not needed for modClark analysis, basin-averaged rainfall can be used for gaged-rainfall forecasts and to compare with radar rainfall measurements. The PRECIP input file, SUBPPT, was constructed during the original model development (section 4.1). SUBPPT must be refined and verified in an operational mode before full implementation.

During an archetypal real-time flood forecasting operation, HEC-1F is run twice. The first execution, labeled the estimation run (E-model), involves runoff parameter calibration. The user then analyzes the calibration results, makes any appropriate zonal parameter changes (loss rates, base flow), and re-runs HEC-1F in the forecast mode (F-model). At this time, modClark does not have the capacity for parameter calibration. There are two possible routes for the forecasting step in modClark real-time operations. The simpler method would be to avoid the parameter estimation and run modClark only once, in forecast mode. The second method would involve running modClark twice, initially to produce the subbasin-averaged radar measured rainfall hyetographs. These would then be used as the precipitation input for an HEC-1F E-model run, yielding calibrated base flow and loss rate parameters. The parameters would then be manually updated in the modClark hydrologic parameter file, and modClark run in forecast mode. Whenever modClark is run in forecast mode, the routing and combining must be executed using the HEC-1F F-model. This will allow for the implementation of the hydrograph blending feature of the real-time water control software. The HEC-1F F-model input file, IBASAE, can be developed through limited modifications to the HEC-1 routing and combining file.

The DSPLAY program is used to graphically display HEC-DSS data (USACE 1994). Macros enable the user to save and reuse a series of DSPLAY input lines and initiate them through a single input. This provides for quick data plotting. DSPLAY macros are contained in the DSPMAC file. A DSPMAC file was used in the development stage of this application. This file should be modified according to District specifications for use in the real-time operation.

This chapter has listed the files necessary for the application of modClark as a real-time flood forecasting tool. Once these files are constructed, however, model development is not complete. Testing must be performed in a fully operational real-time mode for historical recorded events. The validity of Clark's unit hydrograph parameters and Muskingum routing parameters for the real-time model must be evaluated (section 2.6). A fully operational real-time flood forecasting tool is not static; it requires constant performance checks and updates.

Appendix A

References

Clark, C.O. (1945). "Storage and the Unit Hydrograph," *Trans. Amer. Soc. Civil Eng.*, 110, 1419-1446.

Klazura, G.E., and D.A. Imy (1993). "A Description of the Initial Set of Analysis Products Available from the NEXRAD WSR-88 System," *Bulletin of the American Meteorological Society*, 74(7), 1293-1311.

U.S. Army Corps of Engineers (1989). *Water Control Software - Forecast and Operations*, Hydrologic Engineering Center (HEC), Davis, CA.

U.S. Army Corps of Engineers (1990). *HEC-1 Flood Hydrograph Package*, Hydrologic Engineering Center (HEC), Davis, CA.

U.S. Army Corps of Engineers (1991). *Mark Twain Lake Water Control Manual - Salt River Basin, Missouri*, St. Louis District, St. Louis, MO.

U.S. Army Corps of Engineers (1994). *HEC-DSS User's Guide and Utility Manuals*, Hydrologic Engineering Center (HEC), Davis, CA.

U.S. Army Corps of Engineers (1995a). *DATCHK and DATVUE Data Screening Software User's Manual*, Hydrologic Engineering Center (HEC), Davis, CA.

U.S. Army Corps of Engineers (1995b). *GridParm-DEM2HRAP: A Procedure for Evaluating Runoff Parameters for HRAP Cells from USGS Digital Elevation Models - Draft*, Hydrologic Engineering Center (HEC), Davis, CA.

U.S. Army Corps of Engineers (1995c). *GridUtl Gridded Data Utility Program User's Manual - Draft*, Hydrologic Engineering Center (HEC), Davis, CA.

U.S. Army Corps of Engineers (1995d). *modClark Modified Clark Runoff Simulation Users Manual*, Hydrologic Engineering Center (HEC), Davis, CA.

U.S. Army Corps of Engineers (1995e). *Water Control Data System (WCDS) Past, Present, and Future*, Research Document 39, Hydrologic Engineering Center (HEC), Davis, CA.

Walton, M.L., J.A. Smith, and R.C. Shedd. (1988). "NEXRAD Hydrometeorological Processing," *Next Generation Weather Radar (NEXRAD) Hydrometeorology Symposium*, 10/25-26/1988.

Appendix B

Overview of the NEXRAD System

The National Weather Service's (NWS) Weather Surveillance Radar - 1988 Doppler (WSR-88D) is state-of-the-art radar technology applied to meteorology. It provides precipitation measurements on the 4 km Hydrologic Rainfall Analysis Project (HRAP) grid. HRAP is a polar stereographic projection true at 60° North latitude and oriented so that 105° West longitude is parallel to the ordinates of the grid (USACE 1994b). Data is generated for 1-hour, 3-hour, and total event precipitation. Unless otherwise stated, this section is referenced entirely to Walton et al. (1988), who provide a definitive summary of the NEXRAD system.

NEXRAD is a multi-agency effort to develop a nationwide Doppler weather radar system. It was estimated that by 1996, the installation of 136 sites in the coterminous 48 states would be completed (Klazura and Imy 1993). Currently under development, NEXRAD has four stages of data processing within the involved hydrometeorological software. Stage I is performed at the actual NEXRAD site while Stage II is to occur externally at a NWS Warning and Forecast Office (WFO). Stage III will be performed at a NWS River Forecast Center (RFC) for the entire region under the Center's surveillance. Stage IV will be a conglomeration of the previous stages and produce a nationwide hourly precipitation map.

A variety of different processes is involved with each NEXRAD stage. A brief review of those relevant to rainfall-runoff simulation is important to the understanding of the modClark method and its comparison to older techniques. This does not involve processes relating directly to radar measurement techniques.

Stage I is composed of the Precipitation Processing System (PPS) and the Flash-Flood Potential System (FFP). The FFP is not of importance to this study. Within the PPS, there are five functional steps to produce the best estimate of rainfall "relatively cheaply (with respect to computer resources), yet provide an accuracy that make the precipitation estimates useful for local real-time applications" (Walton et al. 1988). Steps one through three involve radar processing and data conversion. The fourth step involves the adjustment of radar estimates based on available rain gage data. This gage adjustment is not yet functional. Due to various radar errors, precipitation estimates can be off in magnitude by a factor of two or more. In most cases, a multiplicative bias occurs uniformly throughout the radar estimated precipitation. A procedure will thus be used to compare the hourly precipitation measurements from specific real-time reporting rain gages within the radar sweep to the associated radar values. A mean-field radar bias is found and applied to the radar data on a periodic basis. If real-time hourly gage reports are available, this procedure is performed hourly. Otherwise, previous real-time bias estimates are propagated forward in time until the next set of gaged data is obtained. The fifth and final step of the PPS involves the updating of the graphical and digital products with the adjusted data.

Due to NEXRAD's present level of development, Stages II and III are currently combined and performed at several of the RFC's. Under the Stage II procedures, satellite and rain gage data are used to detect and correct radar data. Infra-red satellite sensing is used to determine cloud location on a 40 km grid resolution. If the radar measures any rainfall within a 40 km grid-cell where the satellite data shows no clouds and rain gages report no precipitation, the radar data within the cell is set to zero. Radar and rain gage data are merged to form an "optimal multisensor estimate of the rainfall field" (Walton et al. 1988). The procedure was designed to account for the strengths and weaknesses of both the radar and gage systems. The use of a rain gage for radar data adjustment depends heavily on its proximity to the NEXRAD cells in question and the spatial variability of the rainfall involved. In the case of largely spatially varied events, such as convective storms, the rain gages receive lower "weights". For more spatially uniform events, the rain gage network is given more weight.

Stage III involves the "mosaicking" of radar data from different adjoining sites such that the whole area under an RFC will have "continuous" data. Within this stage, there is the possibility for more data refinement. This is performed on a per-need basis, as defined by a forecaster's inspection of the preliminary mosaicked radar/gage and gage rain fields. After mosaicking, Stage III provides mean areal precipitation (MAP) values for the basins and time steps specified by the RFC.